Palm-Integrated Sensors Using Altera FPGA Board

ICS 213

Project Report

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Ilya Issenin
Radu Cornea
Ana-Maria Badulescu

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Introduction

In the increasingly competitive market of today, efficiency is a very important issue. Many tasks previously requiring human intervention are now performed automatically, with the use of embedded systems. Companies can benefit form this, since they require less personal for completing the same tasks.

These tasks can be centralizing data from different sources to a central database, which mean that they require collecting the data, processing it, and sending it to a remote location. Moreover, the source of the data may be located in an isolated area where there is no access to a computer or Internet connection.

Developing such a system from scratch requires a lot of effort, time and money. In our project we show that it is possible to develop such an infrastructure using standard available units like PDAs, FPGA boards with little or no changes at all in a short period of time. For our project, we used:

- Altera FPGA development board
- Palm IIIxe (with IR and serial communication capabilities)
- External modem

Some possible scenarios where such system could be used are:

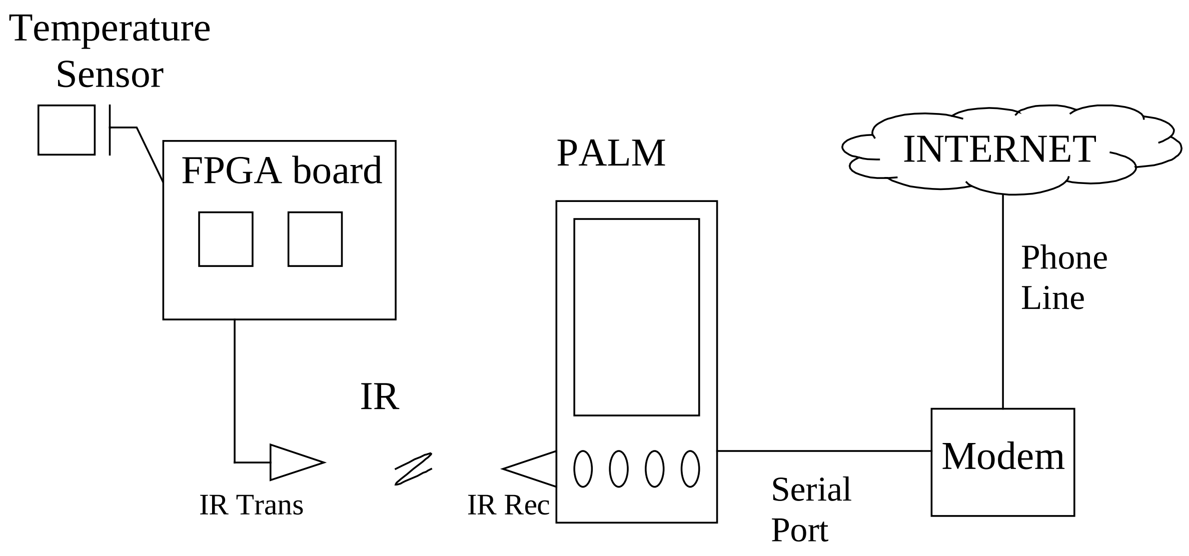
The FPGA board with sensors collects the data for some period of time (i.e. changes of outdoor temperature for a week). We can put multiple boards in different places, where there are no means of transmitting data continuously (no fiber-optic cables, Ethernet or phone connections). Once a week a person visits those sensors, downloads all data to Palm, and after coming back connects the Palm to the Internet, and Palm automatically uploads everything to a server.

The board can be used to monitor certain activities, collect the data and transmit it via IR link to Palm. The Palm periodically uploads the data on a specific server on Internet, via modem connection. If a critical condition occurs and it is detected by Palm, it can go into a different state where it first sends an alert through Internet and then it either remains connected waiting for further instructions (from a human person) or it resumes its normal execution cycle.

As it is shown in the figure below, for demonstration purposes we decided to limit our project to a system that performs the following tasks:

- measures temperature with a sensor connected to the FPGA board;
- sends temperature values to the Palm via IR link, without storing them on the board;
- processes the data on Palm:
    - performs error correction;
    - plots graph with temperature variation over time;
    - sends warning e-mail messages when temperature exceeds certain threshold values;

  - sends collected data from Palm to a server on the Internet via TCP/IP connection. The server processes the data and plots a graph that is posted on the web page.



In order to complete our goal, we needed to complete the following tasks:

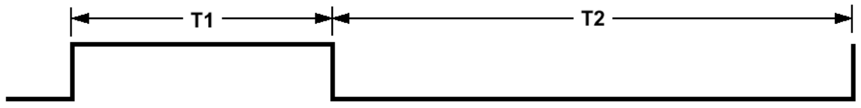
- select a temperature sensor and connect it to the board;
- add IR transmitter to the board;
- design the controlling hardware implemented in the on-board FPGA;
- program the Palm for:
  - support for IR communication between the board and the Palm;
  - support for the Internet connection from Palm through the modem;
- develop a server application for receiving and plotting data;
- design a web page to display the uploaded data.

Chapter 1. Description of the hardware used in the project

Temperature Sensor

We used TMP04FT9 temperature sensor made by Analog Devices. This sensor has a wide temperature range (-40°C to +150°C) with the accuracy ±1.5°C (in -25°C to +100°C range) [13]. The temperature detector has modulated serial digital output, with the ratio of high and low period being directly proportional to the temperature of the device. This significantly simplifies its interfacing to the microprocessorless FPGA board, because it eliminates the need of ADC and calibration procedures (in comparison with thermoresistor) and it doesn't require implementing the two-way protocol in hardware, which we would need to do if we used Dallas Semiconductors i-Button.

The output of the sensor is a square wave with the high and low periods T1 and T2 (see the figure below):



TMP03/TMP04 Output Format

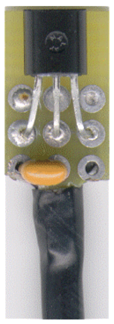
The period T1 is approximately 5 - 15 ms, while T2 varies in 10 – 40 ms interval.

The temperature can be calculated using the following formulas:

$$Temperature(C) = 235 - \left(\frac{400 \times T1}{T2} \right)$$

$$Temperature(F) = 455 - \left(\frac{720 \times T1}{T2} \right)$$

Since both periods are obtained consecutively and the formulas depend on their ratio only, the temperature readings are independent of the drift in either originating clock in TMP04 or the clock of the FPGA board that is used for the period measurements. The sensor is laser-trimmed for accuracy and linearity during manufacture and do not require any further calibration.



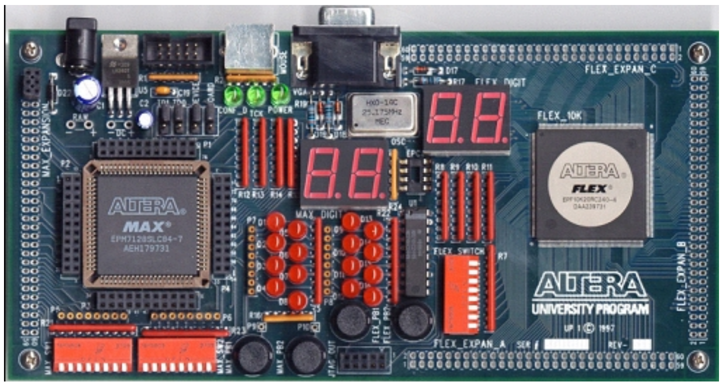
The model TMP04FT9 we use uses TO-92 package, which we mounted on the separate PCB and connected with the main board using 3-wire cable (see figure on the right).

Infrared Transmitter

To send data to the Palm PDA via IrDA link, we used NTE3017 infrared GaAs emitting diode (NTE Electronics, Inc.). Its emission wavelength is 950 nm, angle of half intensity is ±22 degrees and radiant power is 15 mW. The nominal continuous current of NTE3017 is 150 mA, while the output current of FPGA I/O pin is only 25 mA [3]. That is why we had to add a simple, one-stage amplifier (see schematics on the next page).

The infrared diode is mounted on the PCB connected to the FPGA board (figure on the right).

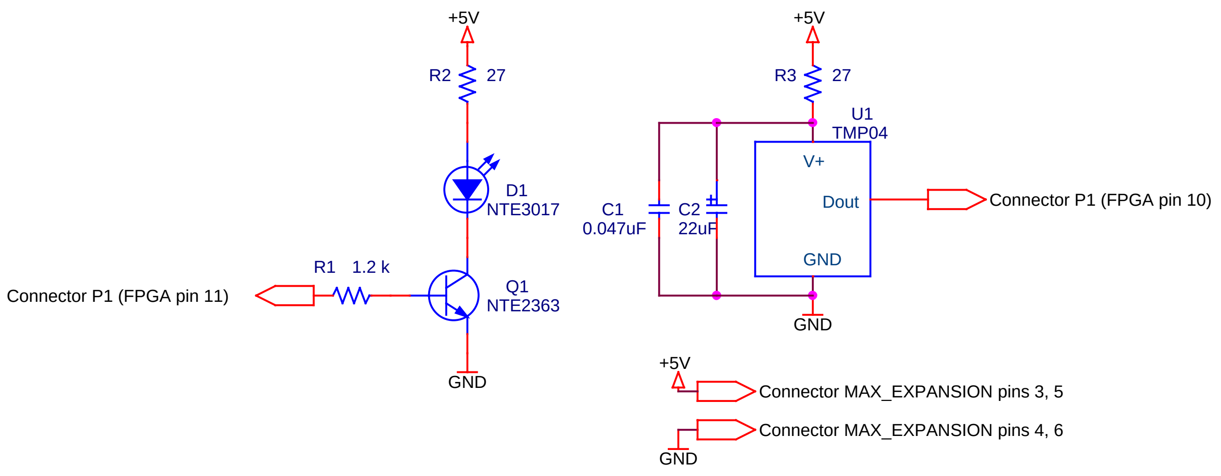
FPGA Board



For processing the signal from temperature sensor and sending the data to the Palm, we used the University Program Design Laboratory Package made by Altera Corporation (figure above). This board contains two FPGAs from MAX7000 and FLEX10K families, several LED displays and switches, and the oscillator [1]. From the board we use only MAX7000 family FPGA (EPM7128S) for processing the data, dual-digit 7-segment LED display for controlling the changes in the temperature (it is displaying the hexadecimal number, proportional to the low-period T2), and oscillator 25.175 MHz as the clock source for the FPGA. We decided to use MAX7000 FPGA because it stores its configuration in the internal EEPROM and does not require special programmer hardware for external EEPROM or computer to download the configuration after power-up. The internal EEPROM of EPM7128S is programmed via FPGA JTAG pins, connected to the printer port of the IBM PC, under MAX+PLUS II software control.

FPGA EPM7128S contain 128 macrocells, each of it consists of one flip-flop and five product terms. The equivalent number of usable gates for this FPGA is 2500.

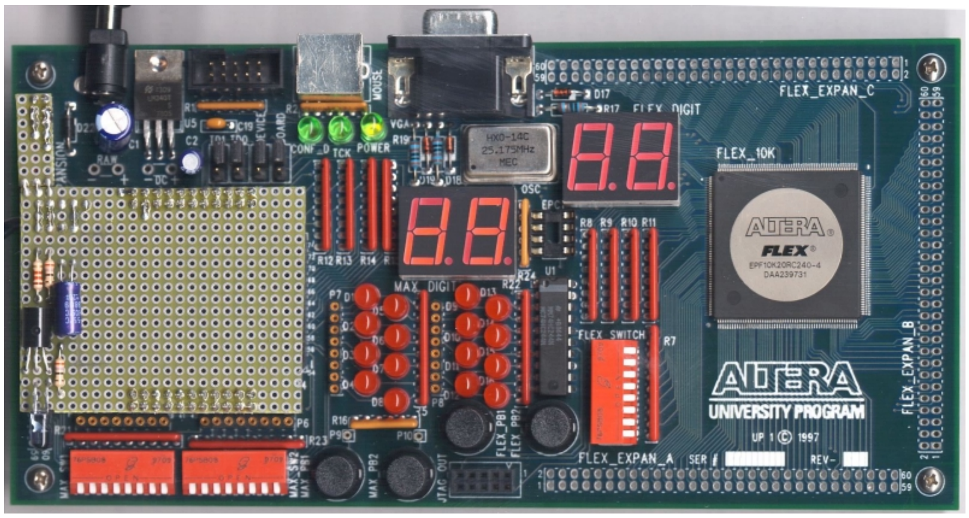
Schematic diagram for the interfacing of the temperature sensor and the infrared transmitter is depicted below:



+5V
R2 27
D1 NTE3017
R1 1.2 k
Connector P1 (FPGA pin 11)
Q1 NTE2363
GND
+5V
R3 27
U1 TMP04
V+
Dout
GND
Connector P1 (FPGA pin 10)
C1 0.047uF
C2 22uF
GND
+5V
Connector MAX_EXPANSION pins 3, 5
Connector MAX_EXPANSION pins 4, 6
GND

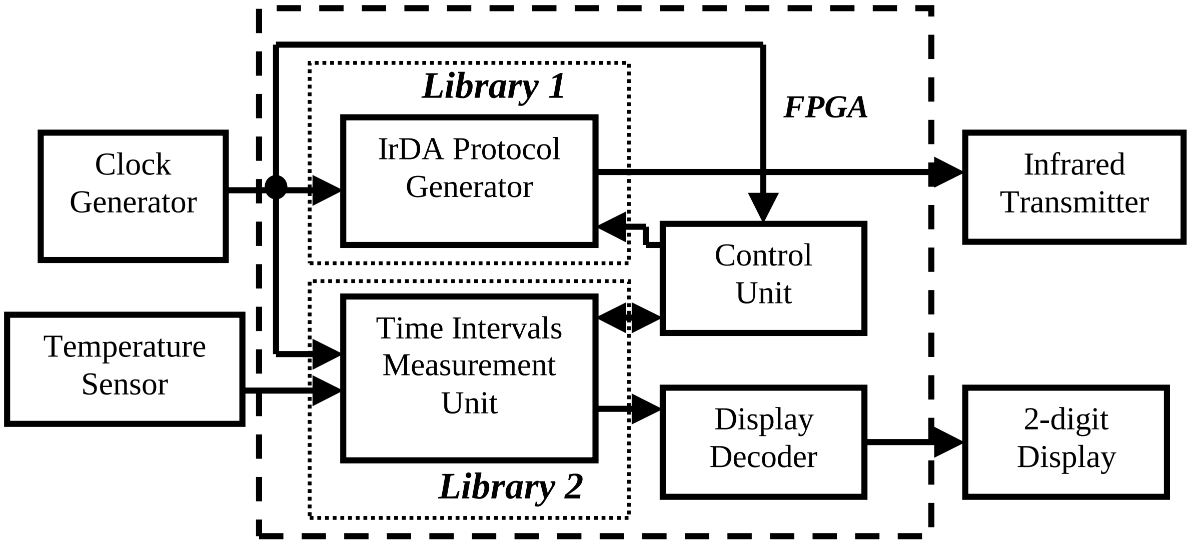
The amplifier for the infrared emitting diode D1 consists of resistors R1, R2 and transistor Q1. R1 limits the value of the output current of the FPGA pin to $I_{fpga\_out} = \frac{Vcc - 0.7V}{R1} = 3.6mA$ and R2 limits the current through LED to $I_{led} = \frac{Vcc - V_{led} - 0.2V}{R2} = \frac{5V - 1.7V - 0.2V}{27} = 115mA$. R3, C1 and C2 form power supply filter for the temperature sensor U1.

All the components except temperature detector U1 and C1 are mounted on the PCB, which is mounted on the connectors P1, P3 and MAX_EXPANTION of the FPGA board [1]. The FPGA board with our PCB attached is shown on the figure below.



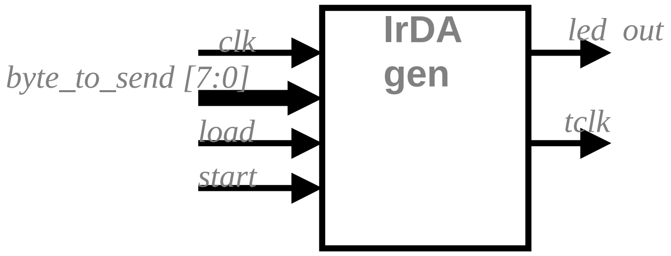
FPGA Programming

FPGA was programmed using MAX+PLUS II software with Verilog hardware description language. The block diagram of the designed hardware is depicted on the figure below.



Clock Generator, Temperature Sensor, Infrared Transmitter and 2-digit Display are located on/connected to the FPGA board and are external as regards to the FPGA chip.

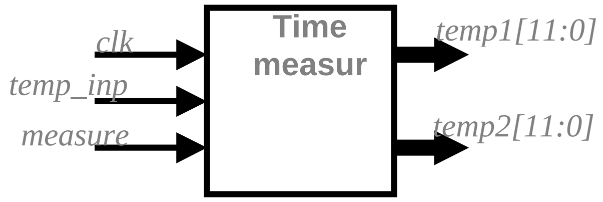
IrDA Protocol Generator has four inputs:



- clk – clock frequency input;
- byte_to_send – 8-bit data input;
- load – when load=1, input data are copied to the internal register from which they will be send using IrDA protocol later;
- start – after setting this input to 1 the data from internal register are transmitted via infrared LED using IrDA physical layer protocol;
- led_out – output to which infrared LED should be connected;
- tclk – output with IrDA_Speed_bod frequency.

This library module has two parameters:

- IrDA_Speed_bod - IrDA transmitting rate, 9600 bod by default;
- Clock_Freq_Hz – on-board clock frequency, 25175000 Hz by default.



Next library module, Time Intervals Measurement Unit (above figure), has following ports:

- clk – input clock frequency;
- temp_inp – signal from the TMP04 temperature sensor;
- measure – when “1”, updates internal registers temp1 and temp2 with the results of high-period and low-period measurements;
- temp1, temp2 – outputs of the internal 12-bit registers which hold the measured value for high-period and low-period signal measurements.

Control Unit synchronizes the work of the previous two modules. The communication protocol it implements (that works over IrDA Physical Layer Protocol) is described later in this chapter.

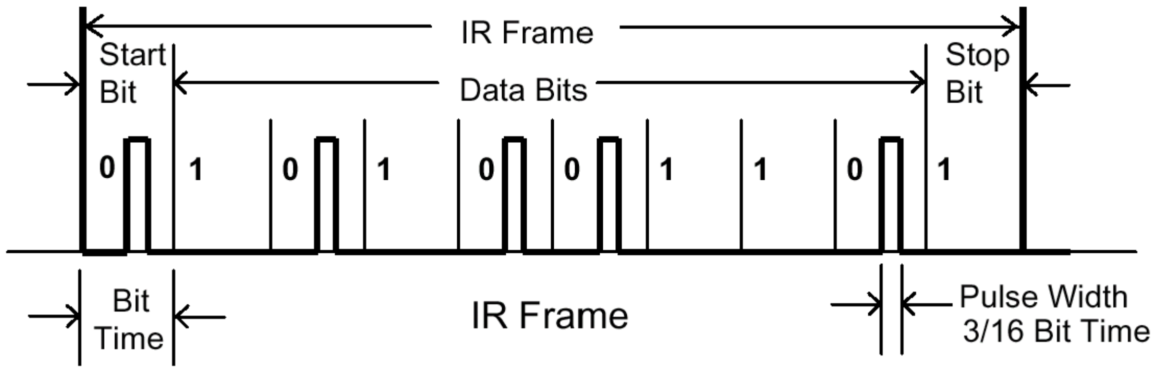
Display Decoder converts the least significant byte of temp2 into hexadecimal representation that is displayed on the on-board 2-digit display.

The total size of the source code is approximately 200 lines, below is some of the statistics reported by the synthesis tool:

Total logic cells used:	123/128 (96%)
Total flipflops required:	89
Total product terms required:	398

IrDA Physical Layer Protocol

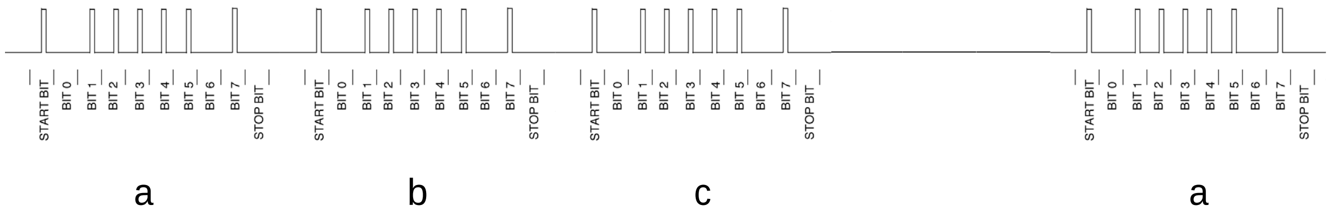
Our FPGA board with sensor sends measured values to the Palm via infrared link using IrDA Physical Layer protocol as a physical layer protocol and communication protocol described in the next section that uses IrDA Physical Layer Protocol as an underlying protocol.



According to the IrDA Physical Layer specification [12] for the signaling rates up to 115.2 kb/s, the data are send as a stream of frames. Each frame consists of Start Bit, 8 Data Bits and a Stop Bit. No Parity Bit is used. All bits are encoded using RZI (Return-to-Zero-Inverted) modulation, that means that “0” is represented by a pulse with a duration of 3/16 of a bit period, and “1” is represented by no pulse. Least significant bit is transmitted first.

We use 9600 b/s transmission rate in our project.

Communication Protocol



The board transmits the 12-bit high and low period values (T1 and T2) as the series of three frames: a, b and c. The value of T1 does not change a lot over the all temperature range, the most significant 4 bits are always staying the same. That is why we transmit only 8 least significant bits of T1.

The meaning of the 8-bit frames is following:

- first byte (a): T1[7:0]
- second byte (b): {000, T2[11:7]}
- third byte (c): {1, T2[6:0]}

For each measurement, two set of frames (a, b, c) are transmitted with the same values. In one second five measurements are made and 10 sets of frames are transmitted.

Chapter 2. IR Communication using Palm

Introduction

Palm PDAs are the handhelds with the high success on the market today. They are easy to use, small and affordable.

All Palm devices have a similar architecture, with small differences in term of size, memory, and other characteristics. They include a LCD touchscreen with a resolution of 160x160, flash ROM, RAM (2/4/8 Mb), Motorola 68328 processor (and newer variants of it), serial peripheral interface (up to 115200 bps), infrared communication support (IrDA capability) and simple sound. The small screen size poses some problems when designing programs for the Palm (user interface).

The PDAs operate using PalmOS operating system, which is based on a real-time multitasking kernel (Kadak). However, only the operating system has access to it, user programs are single-threaded, with only one program being executed at any time. This also imposes some restrictions the programmer has to deal with.

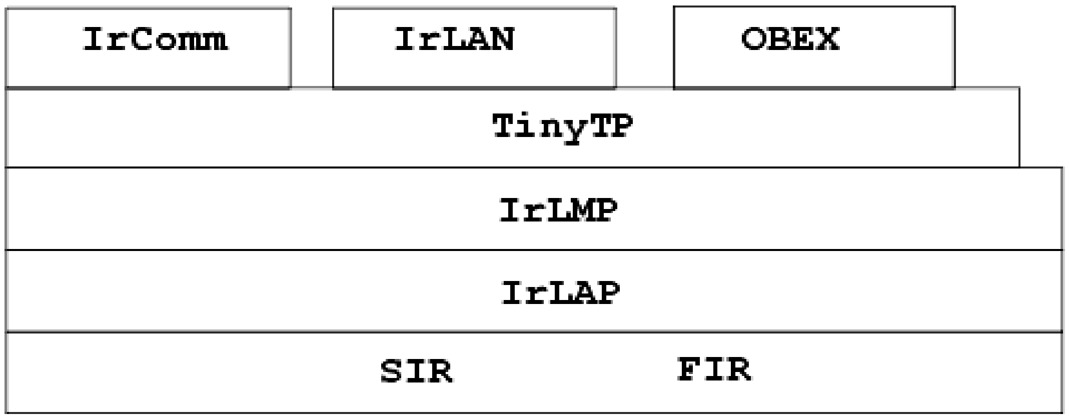
For our implementation we chose Palm IIIxe, one of the entry-level version. This particular device has a monochrome screen, 2Mb of flash ROM, 8Mb of RAM and a Motorola 16MHz MC68EZ328 processor. It runs on a pair of AAA batteries. The low frequency of the processor means that we should try to optimize our programs so that they do not overwhelm the processor. The processor also does not have a floating-point unit (floating point operations are done in software), so floating point computations should be avoided whenever possible.

The operating system running on Palm IIIxe is PalmOS 3.5. Since version 2.0, PalmOS has brought new features to the Palm compatible devices, like infrared capability, serial capability of up to 115200kbps, support for up to 16 gray levels on monochrome screens, etc.)

PalmOS includes a standard TCP/IP stack implementation, which facilitates building networking applications. Connection to external networks (like Internet) can be done using serial modems (built-in support) or directly in case of wireless enabled devices (Palm VII).

Palm IrDA Implementation

The standard IrDA stack comprises a number of protocol layers, of which some are required and some are optional. The complete stack looks like in the figure below:



The SIR/FIR layer is purely hardware. The SIR (Serial IR) layer supports speeds up to 115k bps while the FIR (Fast IR) layer supports speeds up to 4M bps. IrLAP is the IR Link Access Protocol that provides a data pipe between IrDA devices. IrLMP, the IR Link Management Protocol, manages multiple sessions using the IrLAP. Tiny TP is a lightweight transfer protocol on which some higher-level IrDA layers are built.

IrComm provides serial and parallel port emulation over an IR link. IrLAN provides an access point to Local Area Network protocol adapters.

OBEX is an object exchange protocol that can be used (for instance) to transfer business cards, calendar entries or other objects between devices.

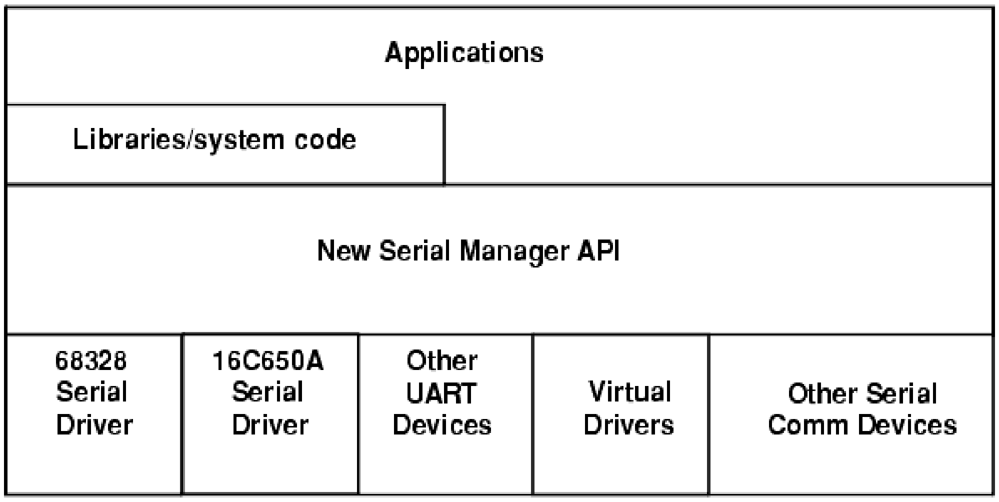
The Palm OS implements all the required protocol layers (SIR, IrLAP, IrLMP, and Tiny TP), as well as the OBEX layer. Palm III devices provide SIR (Serial IR) hardware supporting the following speeds: 2400, 9600, 19200, 38400, 57600, and 115200 bps. The stack is capable of connection-based or connectionless sessions.

From the IrDA layers Palm provides, we use only the lower level, SIR level. In PalmOS, the SIR level of IrDA can be accessed through the New Serial Manager, which is capable of managing multiple serial connections within a Palm device.

The main difference between the new serial manager and previous versions is that the new serial manager supports multiple physical serial hardware devices and virtual serial devices, the detailed operation of which is abstracted from the main serial management code.

The new serial manager manages multiple serial devices with minimal duplication of hardware drivers and data structures. In older Palm systems, the serial library managed any and all connections to the serial hardware in the 68328 (Dragonball) processor, which was the only serial device in the system. Newer systems contain additional serial devices, such as an IR port.

The figure below shows the layering of communication software with the new serial manager and hardware drivers:



The new serial manager maintains a database of installed hardware and currently open connections. Applications, libraries, or other serial communication tasks open different pieces of serial hardware by specifying a logical port number or a four-character code identifying the exact piece of serial hardware that a task wishes to open a connection with. The new serial manager then performs the proper actions on the hardware via small hardware drivers that are opened dynamically when the port is needed.

Once a port is opened, the new serial manager allocates a structure for maintaining the current information and settings of the particular port. The task or application that opens the port is returned a port ID and must supply the port ID to refer to this port when other new serial manager functions are called.

Upon closing the port, the new serial manager deallocates the open port structure and unlocks the driver code resource to prevent memory fragmentation.

From hardware point of view, the UART unit in MC68EZ328 controls the infrared LED/sensor. The UART unit also drives the 5-wire serial interface (used for hotsyncing and for connecting to external devices – modems).

IR Receiver

Receiving the infrared stream of data is relatively simple with the help of New Serial Manager, since it is very similar to standard serial communication. There are functions provided for opening a serial connection, checking availability of bytes in the receive buffer, waiting for a specified number of bytes to come, reading the buffer and closing the connection.

In our case, the communication is unidirectional, the board does not have receive capabilities. It continuously sends the data read from the sensor and formatted according to our protocol.

From the previous sections, the protocol we choose for transmitting the temperature values from the board to Palm consisted of a series of 3 bytes, which we refer to as a,b and c in the next paragraphs.

Besides receiving the data from the infrared port and computing the temperature, the receiver software on Palm should be able to also provide synchronization with the data stream (a, b, c in the correct sequence), correct all the possible errors or signal if something is wrong (e.g.: no data stream is present).

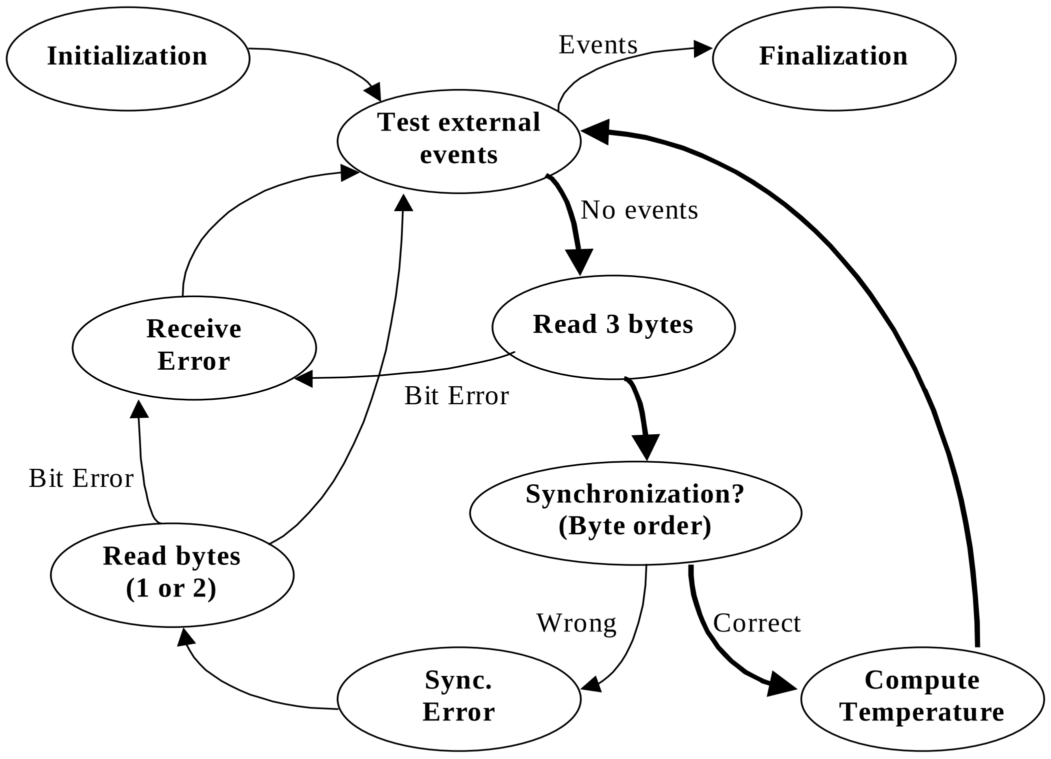
For synchronization, we observe that the three bytes received always have the following properties:

- a – no special property
- b – starts with bit ‘0’
- c – starts with bit ‘1’

Using these properties of a, b, c we can always decide if a sequence of 3 consecutive bytes is in the correct sequence ([a, b, c]) or not ([b, c, a] or [c, a, b]). Moreover, we can take measures to ensure correct synchronization at the beginning of next group of 3 bytes. For that we might need to read additional one or two bytes from the stream.

If for any reasons, during any of the reads we specified above we get an error, the whole process starts from beginning, after signaling the error.

The flow of all operations in the IR receiver is depicted below:



Error Correction

The procedure specified above can detect problems due to the infrared communication. This may not be enough for the purpose of our experiment: even if the bytes are considered to be correct by the IR receiver synchronization algorithm, they may be logically incorrect (e.g.: weak IR transmission, interpreted by receiver in wrong data or packets lost or data out of range due to different factors).

First, we try to remove all values that are obviously out-of-range (e.g. less than -50°C or more than 150°C, which are reasonable values for our experiments, and depend on the application).

The approach we take in case of errors, in order to at least try to recover the good data when possible is relatively simple: collect several sampled values and then sort them and pick the median value (the value in the middle) as the correct sampled value of temperature for that interval.

This procedure can filter most of the errors if they represent less than 50% of all the sampled values. If too many values are out-of-range, then we just mark the sample as invalid (the application that uses these numbers will have to deal with invalid data, either by ignoring it or by using some sort of recovery based on neighbor values).

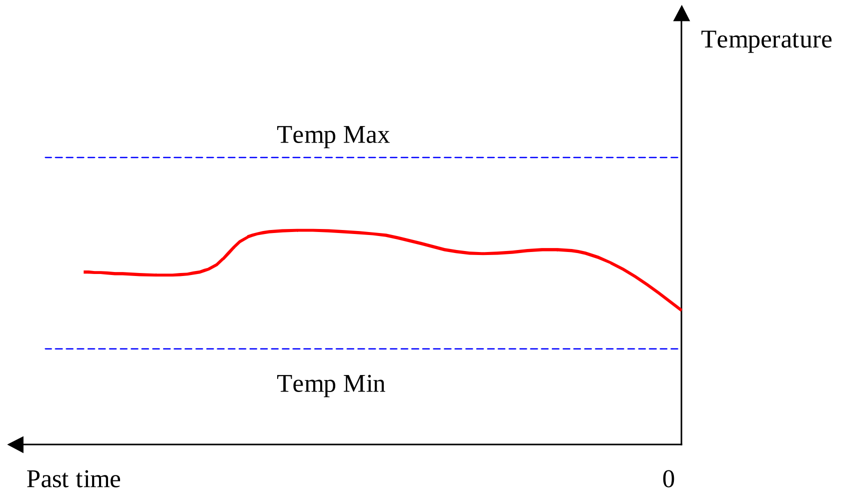
The filtered sampled values are then stored in an internal database, each associated with a timestamp when it was taken.

Temperature Graph

Having the values received form the board and error corrected, we want to dynamically output them on the Palm screen in a graphical way. We have implemented a simple dynamic graph viewer on Palm, which shows the last 130 sampled values of temperature. Due to Palm limited screen resolution we cannot show more than that in a clear way.

The graph is implemented in two separate functions (one that draws the frame, called only once, and another that does the update of the graph, called after each sampling, and optimized for fast response).

The displayed graph looks like in the next figure (there is also a screenshot of Palm showing it)



Temp Max and Temp Min are thresholds used by the temperature monitoring application to trigger some actions when they are crossed (see next chapter).

Temperature Monitoring

In addition to displaying the history of values on the screen, our application also collects all data in an internal database stored on Palm. Periodically, the content of the database is uploaded to an Internet server using the network capabilities of Palm (see next chapter).

Due to a lack of available resources on Palm (there is only one UART unit), collection of temperature values needs to be interrupted during network transmissions and resumed afterwards.

Integration

We grouped the functions handling specific actions into libraries:

IR Sampling library - functions dealing with the infrared communication/data sampling. They provide:

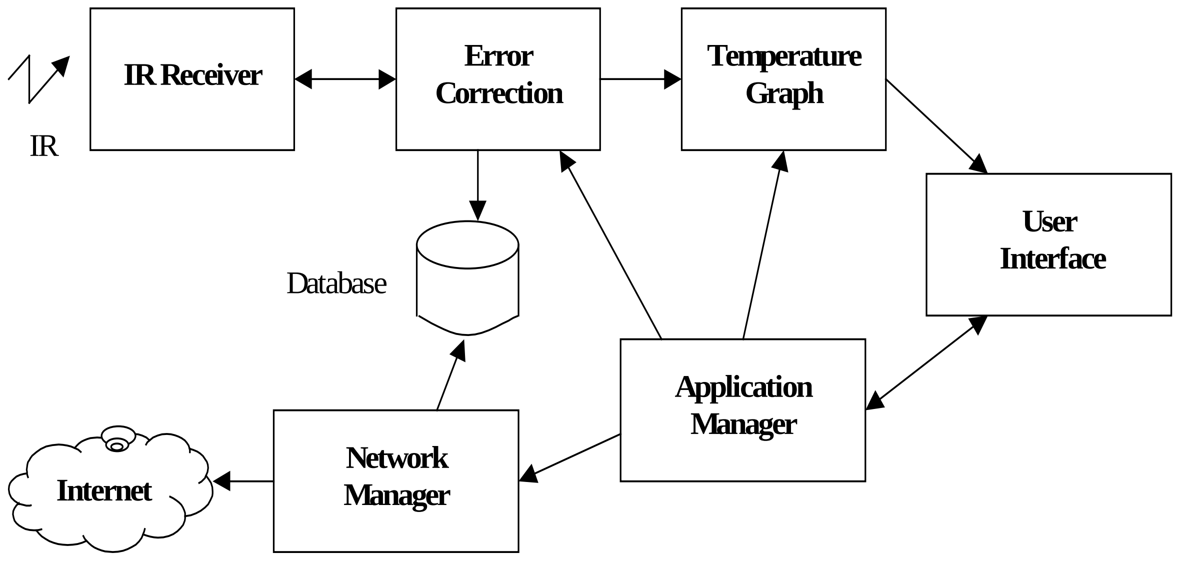
- Initialize IR communication
- Get sample data
- Sort data
- Compute median value
- Verify data validity

- Close IR communication

Functions for drawing the graph:

- Draw frame
- Draw data

All the components described in this chapter have been integrated into a demo application. The structure of the application is presented below:



Chapter 3. Networking

Introduction

The Palm SDK contains a net library that provides network services, like TCP/IP, to applications. With this library, an application on the Palm device can connect to any other machine on a network using standard TCP/IP protocols. The API for this library is a socket interface, modeled very closely on the Berkeley Sockets API.

The similarity between the Berkeley Sockets API and the net library is so close that the Berkeley Sockets source code can be compiled for the Palm OS with minor-and sometimes no-changes. As a result, porting networking code to the Palm OS is very simple. The code can also be ported to any portable Unix-like platforms, like Agenda VR3.

The code was developed on a Unix platform and then just compiled for Palm OS. Much more sophisticated debugging tools are available in the Unix/Linux world than for Palm OS.

Constraints

Currently, TCP/IP communication standard is available only via a serial or modem connection. As mentioned in the previous chapter, IR communication is available only via the serial port. This means that:

- There cannot be IR communication and TCP/IP connection at the same time. Therefore, the TCP/IPC connection starts only when there is data to transmit, or when the user initiates a transfer. It terminates immediately after the data was transferred.
- After the TCP/IP connection is initiated, if any kinds of errors are encountered, our application has to assure that it terminates the TCP/IP connection, in order to unlock the resources, i.e. serial port.

The Client

Our Palm application executes a temperature-monitoring loop. While in this loop, the serial port is used for IR communication with the board. There are 3 situations in which the application can terminate IR communication and start a TCP/IP connection.

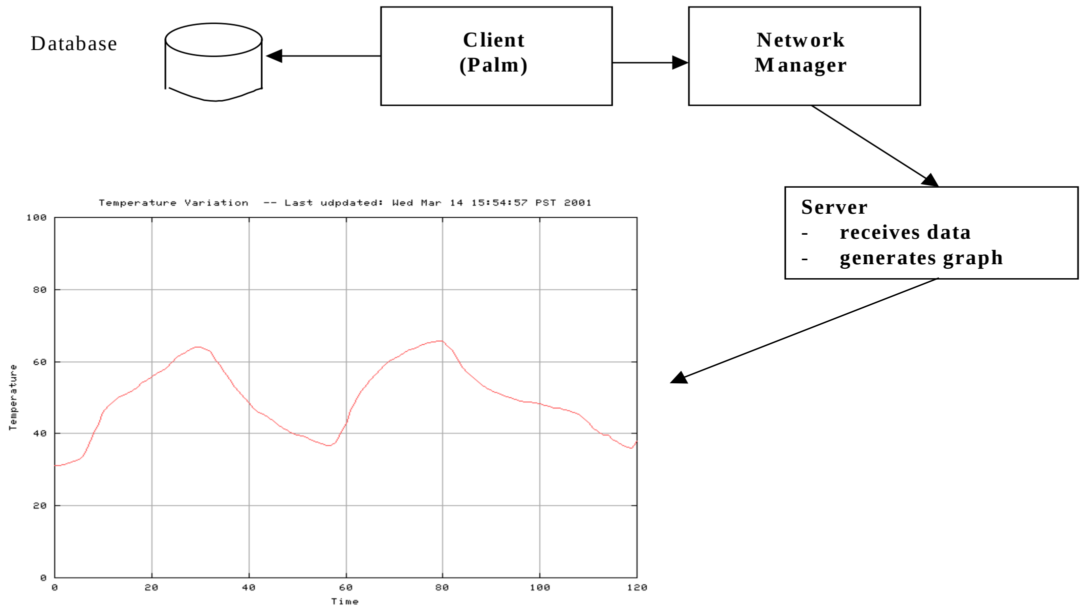
- If the temperature is below or above certain thresholds (current_temp < MIN_TEMP or MAX_TEMP < current_temp), the application sends a warning e-mail message. After that, it waits until the temperature reaches values between the two thresholds. However, in reality the temperature oscillates around values. When for instance MIN_TEMP is reached, the temperature oscillates around MIN_TEMP +/- DELTA_TEMP. This would result in sending e-mails all the time while the temperature gradually increases around TEMP_MIN value. To prevent that, we use a hysteresis, i.e. we do not send e-mails until the temperature is between MIN_TEMP + DELTA_TEMP and MAX_TEMP – DELTA_TEMP.

- The application can upload the collected values of temperature periodically, after an interval specified by the user.
- The application can upload the data at user request. In this case, it will send all the values collected from the beginning of the interval that are stored in the database.

After sending the e-mail or uploading the data (successfully or unsuccessfully), the application terminates the TCP/IP connection in order to free the serial port for IR link. After that, it will resume monitoring the temperature in the loop.

The Server

The functionality of the server is very simple. It receives all the data sent by the client into a text file. Based on this file it generates a graph showing the temperature variation. We used gnuplot for drawing the graph. The image is later included in a web page, updated with the last upload time stamp, and can be accessed on the Internet, with any available Web browser. The Web page of the project is *http://www.ics.uci.edu/~isse/proj213/*.



We developed a simple communication protocol used between the client on Palm and the server for uploading data. The server runs on a Unix host. It uses port number 7002, which should be available. If it is not, the port number can be easily changed.

The figure on the previous page shows the data flow from Palm client to the server, and a sample graph as it appears on the web page.

Functions

We developed a collection of generic functions for basic TCP/IP communications.

```
static int make_connection(char *service, int type, char
*netaddress)
```

/* This is a generic function to make a connection to a given server/port.

service is the port name/number,

type is either SOCK_STREAM or SOCK_DGRAM, and

netaddress is the host name to connect to.

The function returns the socket, ready for action.*/

```
static int atoport(char *service, char *proto)
```

/* Take a service name, and a service type, and return a port number. The number returned is byte ordered for the network. */

```
static struct in_addr *atoaddr(char *address)
```

/* Converts ascii text to in_addr struct. NULL is returned if the address can not be found. */

```
static int sock_gets(int sockfd, char *str, size_t count)
```

/* This function reads from a socket, until it receives a linefeed character. It fills the buffer "str" up to the maximum size "count". This function will return -1 if the socket is closed during the read operation.If a single line exceeds the length of count, the extra data will be read and discarded */

```
static int sock_puts(int fd, char *body)
```

/* This function writes to a socket all the newline-terminated lines contained in body. This function will return -1 if the socket is closed during the write operation.*/

Using the above functions, we developed two more complex functions, which are also very general: sendmail() and senddata(). In order to maintain the generality of these functions, two of the parameters are pointers to functions for printing the status and error message. These functions are platform dependent.

```
typedef void   (*StatusCallbackFunc)(char *status);
typedef void   (*ErrorCallbackFunc)(char *problem, char
*extraInfo);
```

```
int sendmail(char *smtpHost, char *from, char *to, char
*subject, char *data, StatusCallbackFunc statusFunc,
ErrorCallbackFunc errorFunc)
```

/* Sends e-mail to a user by connecting to the STMP server smtpHost. From, to and subject are self-explanatory. data is the body of the message. statusFunc and errorFunc are explained above. */

```
int senddata(char *Host, char *port, struct pair data[], int
N, StatusCallbackFunc statusFunc, ErrorCallbackFunc
errorFunc);
```

/* Sends N elements of data to a server at Host and port. */

Conclusions

We provided the infrastructure for monitoring, processing and publishing sensor data.

We connected the temperature sensor and IR transmitter to FPGA board. The temperature data acquisition is displayed on the board, as well as transmitted to the Palm via IR link.

For programming the board we developed an IrDA_generator library and a Temperature_Measurement library.

Programming the Palm provide:

- IR communication with the board
- Error correction
- IR communication library
- Graph display – generic functions for drawing
- Internet communication using Palm and modem
- Generic communication functions
- Send mail and Send data

We integrated all the components and developed a demo application that shows all the capabilities described above.

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